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EVALUATION OF THE DECOMPOSED *J*-INTEGRAL IN 3D CRACK FRONTS USING COHESIVE ELEMENTS

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ABSTRACT

The assessment of energy available for crack growth can be made by means of the *J*-integral approach. The path-independent contour *J*-integral was first introduced by Rice [1] for two-dimensional problems (either plane strain or plane stress conditions). However, the extension of the *J*-integral for 3D crack fronts is not straight-forward. In 3D crack problems, the path independence of the contour integral is only preserved if the contour is infinitely close to the crack tip. Obviously, the application of this crack-tip contour integral requires accurate computations on the stress field at the crack tip, which is hard to deal with in a finite element framework. Nevertheless, Blackburn [2] derived a generalization of the *J*-integral for a three-dimensional application (or for an inhomogenous or non-elastic material) by applying the divergence theorem to the contour integral. The result is a path independent combination of a contour integral and a surface integral defined over the area enclosed by the contour. This area contains the crack tip singularity and, thus, the numerical evaluation of the surface integral requires, again, the accurate computation of the contribution made by the crack tip elements [3].

However, the evaluation of the 3D *J*-integral becomes easier in a cohesive zone model, since the crack tip singularity is removed by considering a damage process zone (also called cohesive zone) ahead of the crack tip where the cohesive stresses, μ, are function of the separations between crack faces, λ [4]. An example of a linear cohesive law is represented in Figure 1. Moreover, if the path independence of the *J*-integral is employed to shrink the integration contour to the cohesive interface (Figure 2), as Rice [1] already did for its evaluation in 2D cohesive zone models, the surface integral vanishes.

On the other hand, the evaluation of the mode-decomposed *J*-integral in a 3D crack front requires the proper identification of the crack growth direction, usually assumed to be normal to the crack front. However, in a finite element framework, the crack front shape is not an information available at an element level. Furthermore, the crack front shape rendering by exchanging information between adjacent elements is a high computational time-consuming task.

For this reason, in this work a crack propagation direction criterion evaluated at a pointwise level is formulated. The criterion is implemented together with a cohesive zone model formulation [5,6] and searches the direction that minimizes the ratio between the specific

dissipated energy (ω_d in Figure 1) and the fracture toughness ($\mathcal{G}_c$ in Figure 1). The main advantage of this novel formulation is its efficiency, since it only relies on information available at element level. Both the prediction of the crack propagation direction by means of the developed criterion and the direction normal to the crack front shape lead to coincident results in a 3D delamination simulation with finite elements using a cohesive zone model approach.

Finally, the criterion presented has been used to compute the mode-decomposed *J*-integral in several specimens under different mode ratios (I, II and III). Good agreement with the results obtained with the VCCT predictions are obtained.

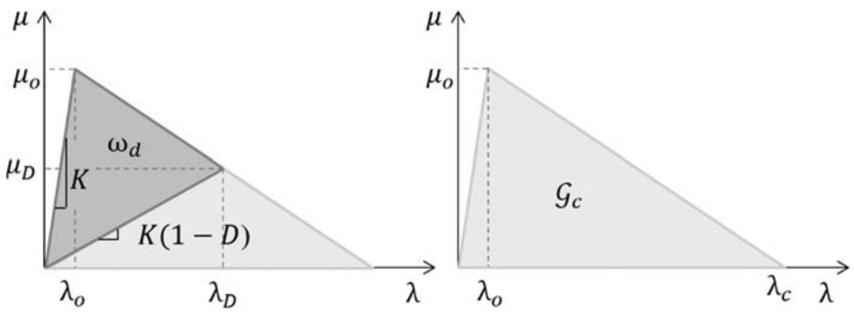

Figure 1: One-dimensional cohesive law for mixed-mode quasi-static delamination propagation simulation.

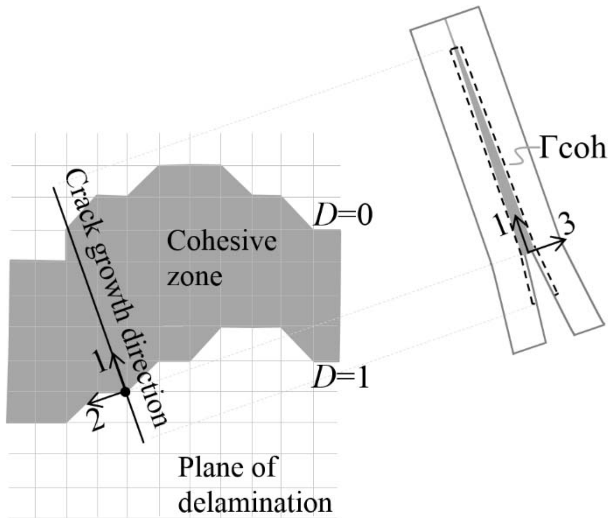

Figure 2: Integration contour of the *J*-integral in a 3D cohesive zone model.

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